

# Coincident radio frequency and optical emissions from lightning, observed with the FORTE satellite

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**Abstract.** We present long optical and radio frequency (RF) time series of lightning events observed with the FORTE satellite in January 2000. Each record contains multiple RF and optical impulses. We use the RF signatures to identify the general type of discharge for each impulse according to the discrimination techniques described by *Suszcynsky et al.* (2000) and reviewed herein. We see a large number of paired, impulsive events in the RF which allow us to study the heights within clouds of several events. We also see that the rate of RF/optical coincidence depends on the type of discharge: nearly 100% of VHF signals from first negative return strokes have an associated optical signal, whereas a mere 50% of impulsive intracloud events appear to have an optical counterpart. While the RF signals from ground strokes clearly coincide with simple optical signals in almost all cases, the intracloud lightning often shows nearly continuous, complicated RF and optical emissions which do not cleanly correlate with one another. The RF and optical pulses do not show a well-defined relationship of intensities, for any lightning type. The observed delay between the RF and optical pulses we interpret as mainly an effect of the scattering experienced by the light as it traverses the cloud. For intracloud lightning, we find no evidence of an intrinsic delay at the source between the onset of the RF and optical signals. Impulsive in-cloud RF events are seen to occur on average every 0.9 ms during a flash.

## 1. Introduction

Los Alamos and Sandia National Laboratories built the FORTE satellite and launched it in 1997. FORTE carries a suite of detectors that monitor lightning activity, and unlike previous lightning monitors, FORTE's instruments can record both the radio frequency (RF) and optical emissions from transient events in the Earth's atmosphere, on a routine, automated basis. Such a dual-phenomenology approach to lightning detection results in a unique combination of lightning and thunderstorm monitoring capabilities. Studying correlated optical and RF emissions from individual lightning events allows the RF signal to be used as a time fiducial, which facilitates estimation of the scattering delay of the optical signal by intervening clouds.

The optical signals from lightning have been compared to lightning  $E$  field changes a number of times. *Beasley et al.* [1983], for example, compared  $\Delta E$  with light from stepped leaders, finding that pulses in each signal were simultaneous to within their measurement accuracy ( $\pm 0.2 \mu\text{s}$ ), although not every  $\Delta E$  pulse showed corresponding light. *Guo and Krider* [1982] studied return strokes and found the light signal to begin at or just after the  $E$  field peak, and they also found that the optical peak is always greater for initial return strokes than for subsequent strokes. *Ganesh et al.* [1984] similarly studied return strokes and saw a correlation (with significant scatter) between  $E$  field intensity and light intensity. *Goodman et al.* [1988] observed optical pulses and  $E$  field changes, allowing them to study optical pulse characteristics as a function of lightning type. In this work, we hope to see what general trends

exist between VHF and optical lightning emission, as a function of lightning discharge type. A few previous studies [e.g., *Christian et al.*, 1983] have compared RF and optical lightning emissions. *Mazur et al.* [1995] compared high-speed video observations and those from a VHF interferometer and saw temporal structure in the optical component of leader activity. *Suszcynsky et al.* [2000] presented the first satellite-based comparison of optical light curves and RF power time series using data from the FORTE satellite. We now continue that work with a systematic comparison of VHF and optical emission as a function of lightning types.

## 2. Data

### 2.1. Detectors

The FORTE Optical Lightning System (OLS) consists of two optical transient detectors. One is a fast broadband photometer (the Photodiode Detector (PDD)), which records time series of events with 15- $\mu\text{s}$  resolution (for greater detail, see *Kirkland et al.* [1998] or *Suszcynsky et al.* [2000, 2001]). The PDD is sensitive from 0.4 to 1.1  $\mu\text{m}$  and records a light curve for events occurring within its 80° field of view ( $\sim 1200\text{-km}$  footprint on the ground). (The OLS has a smaller field of view than the RF receivers, and therefore the RF/optical coincident data are limited to events occurring within this footprint.) The second optical detector on FORTE is the Lightning Location System (LLS), a 128-pixel by 128-pixel CCD array that can geolocate events to within 10 km on the ground (see *Suszcynsky et al.* [2001] for details). The LLS instrument consists of a front-end optical assembly, a fixed-position CCD focal plane assembly with drive electronics, and a Sandia-developed operations and signal processing module for lightning data discrimination. The front-end optical and CCD assemblies are iden-

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tical to those used on the Lightning Imaging Sensor (LIS) developed by the National Aeronautics and Space Administration/Marshall Space Flight Center (NASA/MSFC) [Christian *et al.*, 1992].

FORTE also carries three RF receivers, two of which are described elsewhere [Jacobson *et al.*, 1999]. Since January 2000, FORTE VHF data have been collected exclusively with the third, a broadband radio receiver with an analog bandwidth of 85 MHz and which digitizes at 300 megasamples per second (for a temporal resolution of 3.33 ns). It can trigger autonomously, or it can be slaved to trigger only when the LLS triggers. In the slaved configuration, whenever the LLS detects an event, both the PDD and the RF trigger, and the 8.7 ms (RF) or 6.85 ms (PDD) of data preceding the trigger are recorded as the event. In this present work, we consider the slaved PDD data and the low-band slaved RF data. In this frequency range, the RF is heavily contaminated by anthropogenic carrier signals, however, so that we restrict ourselves to data in the 29- to 49-MHz subband in the RF.

## 2.2. Data Selection

Because all the data in this present study were collected with the optical and RF detectors in slave mode, we are guaranteed to have a geolocation for every data record. However, the LLS is sensitive to glint (e.g., off of the satellite or off of water), cloud albedo, and energetic particles. We therefore found all the slaved data archived from January 2000 and rejected first any nonlightning LLS events. We next rejected daytime events, as the FORTE optical nighttime data are higher quality than daytime data. (We can set the triggering thresholds lower for nighttime data collection, and therefore the nighttime data set is less biased toward very bright events, as well as being less subject to trigger on glint or cloud albedo.) Finally, we rejected any event where the RF was contaminated by radar signals.

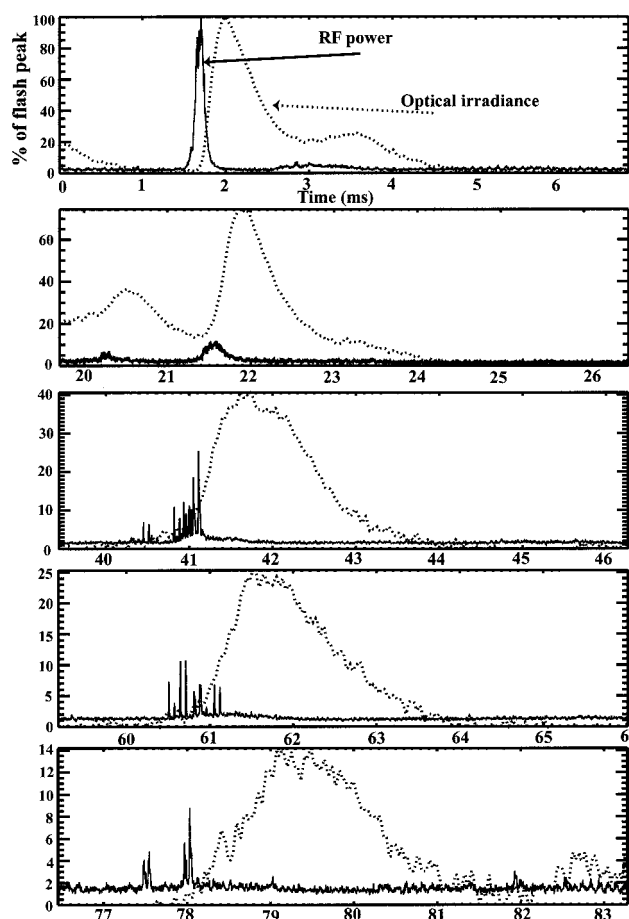
We were left with 222 high-quality RF/optical coincident records. Often, several records occur sequentially, within a few hundred milliseconds. We examined the distribution of inter-record times for all the sequentially recorded RF-optical coincident records whose LLS geolocations indicate they are less than 50 km apart, from data taken between January and April of 2000. It appears that records further than  $\sim 500$  ms apart are not associated with one another, whereas more tightly spaced records can be grouped into flashes. Thus spatially collocated data records which are spaced in time by less than 500 ms we assume to be subsequent triggers from a single flash.

Figure 1 illustrates a data set for a single flash, in which we obtained five records within 86 ms. However, FORTE cannot retrigger instantaneously, but rather there is a delay after each record at least equal to an individual record length. Therefore our flash length data sets are actually made up of snapshots within the flash. For example, in Plate 1 it is clear how these five events, while seen sequentially by the satellite, do not offer a complete picture of the flash.

## 2.3. Data Processing

These FORTE RF power time series have 2,621,440 points with  $\sim 3$ -ns resolution, spanning  $\sim 8$  ms. We bin this data to  $1\text{-}\mu\text{s}$  resolution to create a more manageable data file, in which we can study correlations of RF events with individual optical pulses, as a function of RF event type. First, however, each record must be processed and individual discharges identified.

Each record is examined in turn. We first prewhiten and dechirp the RF spectrogram, as described in detail by Jacobson

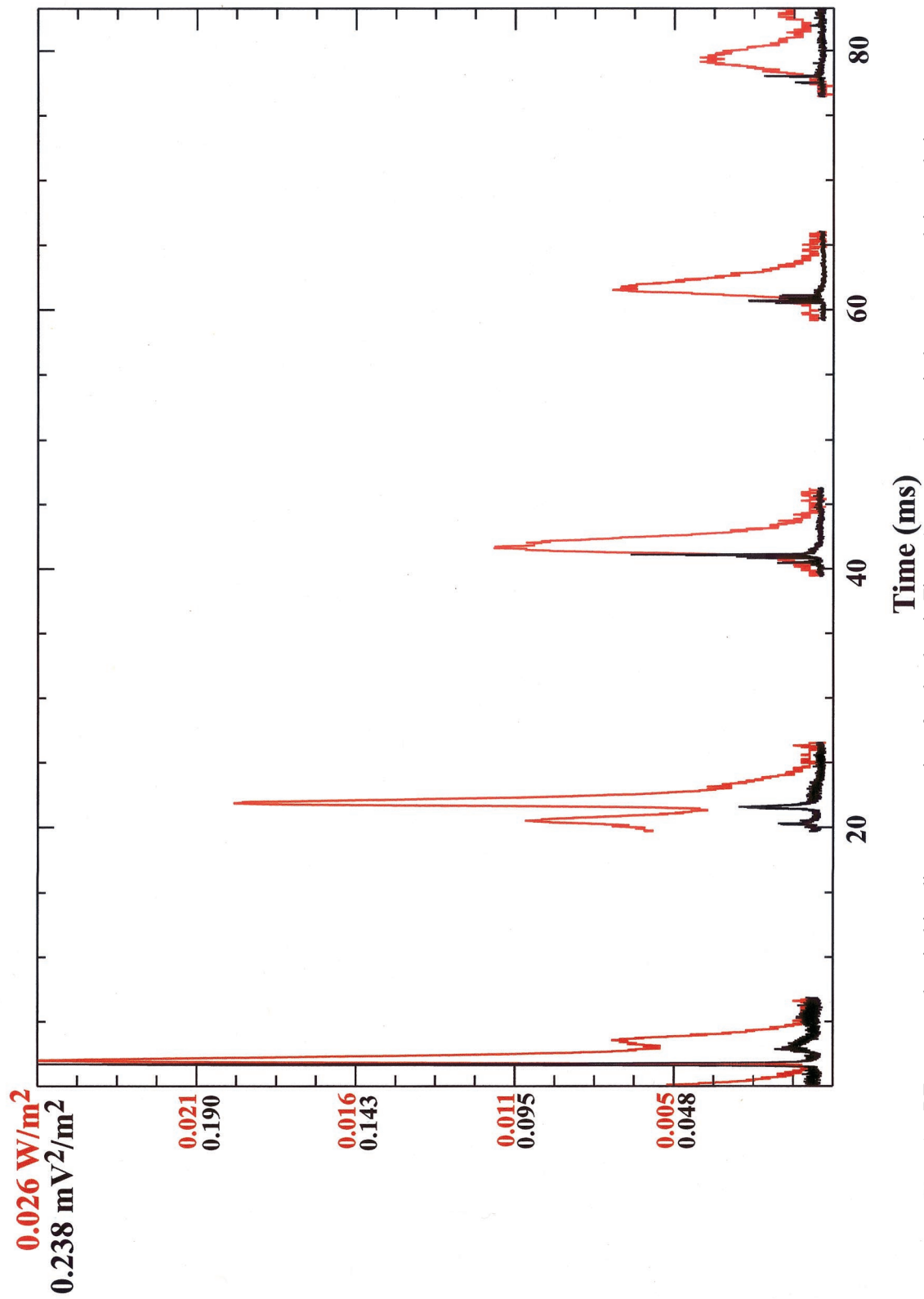


**Figure 1.** Example of coincident RF/optical data from FORTE for a flash in which the detectors triggered five times within 86 ms; the vertical units are arbitrary, as the records have been normalized in order to show the optical and RF intensity of each feature relative to the brightest features in the flash group. The RF and optical data have  $2\text{-}\mu\text{s}$  and  $15\text{-}\mu\text{s}$  resolution, respectively. CG, cloud to ground; IC, intracloud; RS, return stroke.

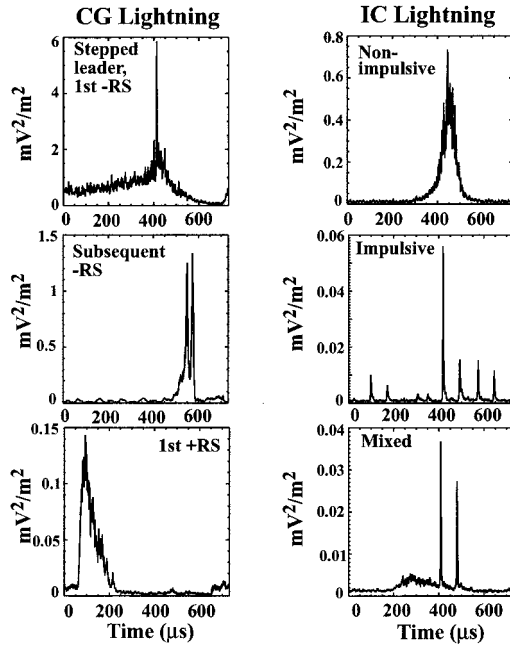
*et al.* [1999], to remove anthropogenic RF carrier bands and the frequency-dependent ionospheric dispersion of the RF signal. The resulting “clean” spectrogram is then averaged over frequency, returning a simple RF power time series for the event. The optical data are recorded as simple time series of optical irradiance and are therefore used in their original state.

Suszcynsky *et al.* [2001] describe a technique to discriminate intracloud from cloud-to-ground discharges in FORTE RF data. This procedure was created specifically with reference to the shorter ( $800\text{ }\mu\text{s}$ ) RF records collected by FORTE. Each of the longer records studied in this present work, however, generally include multiple discharge events (see, e.g., Figure 1). We therefore could identify several individual events within each long record; within these 222 records, we identified a total of 647 individual events. Briefly, we differentiate various lightning events based on the RF power time series as follows (see Figure 2 for an example of each type):

1. There are three types of cloud-to-ground activity: (1) initial negative return stroke: steady increase of RF signal over 1 ms or more (leader activity) with a sharp increase at the time of attachment and a fairly quick recovery to background levels; (2) subsequent negative return stroke: wide events (up to 500



**Plate 1.** RF power and optical irradiance versus time, for the data in Figure 1, presented on a single, compressed timescale in order to show when the five events occurred in relation to one another over the span of 86 ms.



**Figure 2.** Examples of each type of event identified with our discrimination techniques.

$\mu\text{s}$ ) with a very sharp falloff; (3) initial positive return stroke: wide events (up to 500  $\mu\text{s}$ ) with a very sharp onset (no leader activity).

2. There are three types of in-cloud activity: (1) impulsive: narrow events (less than 50  $\mu\text{s}$ ) which rise to several times the background level (signal-to-noise ratio of  $\geq 5 \rightarrow 10$ ); (2) non-impulsive: general in-cloud events that are broad (up to 500  $\mu\text{s}$ ) with a slow rise and slow fall; (3) mixed: events which show a nonimpulsive event underlying one or more impulses.

A number of previous studies have examined the VHF radiation from strokes to ground [e.g., *Le Vine and Krider, 1977; Proctor et al., 1988*]. Both *Hayenga [1984]* and *Shao et al. [1995]* saw VHF leader activity similar to that shown here preceding initial return strokes.

We use the term “nonimpulsive (NI) event” loosely to mean any sort of temporally diffuse, in-cloud event which does not show the sharp onset or cutoff typical of a ground stroke, as found by examining the National Lightning Detection Network (NLDN) coincidence with FORTE RF data. The three classifications of in-cloud events are simply phenomenological descriptions of the three main types of events seen in the data. They are assumed to be in-cloud activity because in the rare

instance such an event is coincident with an NLDN event, it is either unclassified or classified as intracloud (IC) [*Suszczynsky et al., 2001*]. Further, the impulsive events often occur in pairs and are events which the satellite sees both directly and in reflection off the ground; that is, these events occur at some altitude [*Massey et al., 1998*]. Thus while we are confident that these events represent in-cloud activity, we do not have supplemental  $E$  field change or interferometric data with which to relate them to specific in-cloud discharge processes. We also cannot be certain during which phase of a flash they occurred. We speculate that this class of events must include a number of phenomena, such as the K changes described, for example, by *Uman [1987]*. We note, however, that K changes typically are spaced in time by a few to several milliseconds, whereas in these data we often see NI events spaced by only hundreds of microseconds, or less.

The optical pulses also must be individually measured. Often an optical record includes several optical signals, blended to create a broad multi-peaked light curve. As a result, we cannot measure the width of individual curves down at the 20%-of-peak level. Thus in order to get some idea of the rise time and width of individual optical pulses, we fit a parabola to each peak and calculate rise times and widths on the basis of these fits. Widths estimated in this way are not truly representative of the pulse width, since the parabolic fit will neglect the long tail of the optical pulses. However, this allows us an internally consistent measure of optical pulse parameters.

### 3. Comparing RF and Optical Pulses

While identifying individual RF events and individual optical pulses, we also paired them on the subjective basis of whether the optical pulses appeared to coincide with the RF. For example, let us reconsider Figure 1. In the earliest record, there appear to be two RF and two optical pulses, although the second RF event is so broad and weak that it is not measurable. The next two records again show a pulse-for-pulse coincidence. In the fourth record, however, the RF “pulse” associated with the optical signal is in fact several impulses occurring over  $\sim 600 \mu\text{s}$ . The final record shows two distinctly separate, weak pulse pairs in the RF and a broad, weak optical signal. Which pulse pair, if either, is directly associated with the optical signal is unclear, and therefore we measure the RF and optical events, without assigning them as a matched RF/optical set.

The disadvantages of our procedure are obvious. First, it is subjective and phenomenological. Second, we are biased to labeling as pairs those events in which the RF signal precedes the optical, because the optical signal is scattered and delayed

**Table 1.** General Statistics of Individually Measured Pulses

Event Type	$N_{\text{RF}}$	$N_{\text{with opt.}}$	RF Peak, $\text{mV}^2/\text{m}^2$	Optical Peak, $\mu\text{W}/\text{m}^2$
All CG events	96	81	$0.60 (0.22) \pm 1.2^a$	$697 (205) \pm 958^a$
First return stroke	45	45	$0.73 (0.40) \pm 1.1$	$1066 (487) \pm 1097$
Subsequent return stroke	16	11	$0.71 (0.13) \pm 1.8$	$77 (57) \pm 56$
First and return stroke	35	25	$0.39 (0.11) \pm 0.79$	$304 (176) \pm 503$
All IC events	423	221	$0.15 (0.057) \pm 0.30$	$169 (83) \pm 320$
Impulsive	216	81	$0.12 (0.054) \pm 0.25$	$84 (49) \pm 95$
Nonimpulsive	173	113	$0.20 (0.070) \pm 0.37$	$239 (116) \pm 423$
Mixed	33	27	$0.082 (0.055) \pm 0.083$	$132 (83) \pm 143$
Untyped (optical only)	0	128	...	$161 (57) \pm 437$

<sup>a</sup>Values shown are mean (median)  $\pm$  standard deviation.

as it traverses the cloud, and therefore even if it were emitted exactly coincidentally with the RF, it would be observed as delayed. Finally, the lack of a counterpart for any RF or optical event in our database does not absolutely mean that there was no such counterpart, merely that it could not be identified clearly enough.

We therefore offer the following caveat to our RF/optical correlations. The RF/optical coincidence for ground strokes was quite clear; typically, for ground strokes, neither the RF nor optical signals were cluttered, and both were strong. For impulsive in-cloud events, however, the RF/optical correspondence was seldom clear; hence we probably have some number of pairings in the database which are loosely related at best.

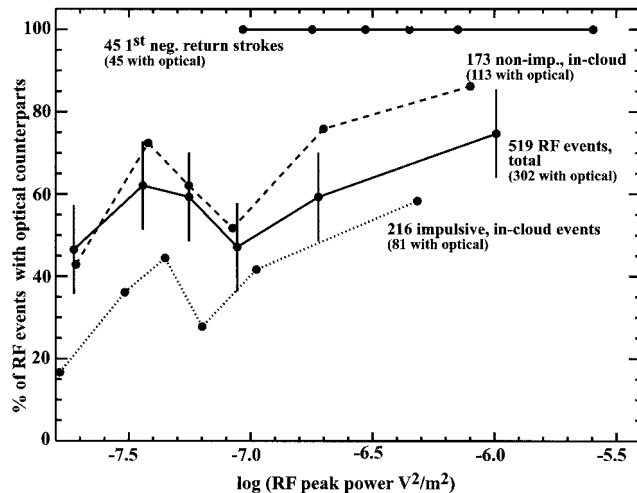
### 3.1. General Statistics

Table 1 lists some statistics, grouped by event type: 647 individual events were measured in the 222 files; 217 were RF signals without an optical counterpart, 128 were optical signals without an RF counterpart, and 302 were events for which both an optical and RF signal was present and measurable. Of the 45 initial negative return strokes identified, 100% showed optical counterparts. For ground strokes in general, ~84% have optical counterparts. Compare this with ~52% for in-cloud lightning. Furthermore, the in-cloud lightning is more likely to be contaminated with random, apparent RF/optical coincidences, owing to the diffuse, quasi-continuous nature of the in-cloud RF emissions and the consequent difficulties in associating a string of RF impulses with an optical pulse. Thus ~52% must be considered an upper limit to the RF/optical coincidence rate of IC lightning.

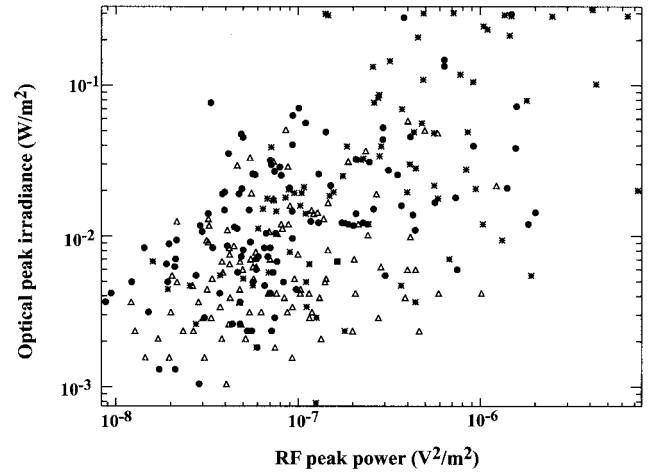
One may wonder whether the slight difference shown among types in Table 1 for the peak RF power (it is slightly higher for first return strokes) is responsible for the differentiated incidence of optical counterparts. Yet Figure 3 shows that regardless of peak power, it is mainly the type of RF event and not the RF intensity that determines the optical coincidence rate.

### 3.2. RF Versus Optical Power

There is no detailed correspondence between the RF and optical pulse peak intensities in the data. This is presumably due in part to the considerable variability of optical scattering



**Figure 3.** Percentage of RF events that have optical counterparts, as a function of RF event type and RF peak power (actually the square of the  $E$  field,  $E^2 \sim V^2/m^2$ ).



**Figure 4.** Optical peak irradiance versus RF peak power ( $E^2 \sim V^2/m^2$ ), differentiated by event type. Asterisks indicate ground strokes, triangles indicate impulsive cloud events, and circles indicate nonimpulsive cloud events.

losses across a range of cloud types; depending on the event's placement in a cloud, the cloud optical depth, and the observer's viewing angle, the same event could be attenuated in observed peak amplitude by up to 2–3 orders of magnitude [Thomason and Krider, 1982; Koshak et al., 1994; Light et al., 2001]. In Figure 4 we see that the observed RF and optical peaks do broadly correlate, but with considerable spread. Here again we see a slight differentiation by event type, with ground strokes somewhat stronger in both types of emission.

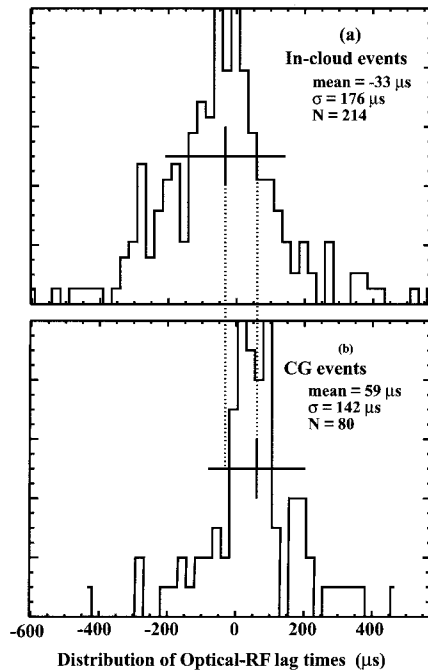
### 3.3. Effects of Optical Scattering

We use the peak of the RF signature from the lightning as a time fiducial in order to estimate the delay of the optical signal due to scattering by clouds. For the case of return strokes, we might assume that there is an additional delay between the RF and the optical emission which is the time necessary for current to propagate up the channel, after the return stroke attachment, back into the cloud, from whence the optical emission is detected; this delay is presumed to be of the order of 50–100  $\mu$ s (see, for example, Ganesh et al. [1984] and references therein). Thus we can estimate the contribution to the observed RF-optical delay which is due to scattering [Suszcynsky et al., 2000]:

$$\Delta t_{rf-opt} = \Delta t_{physical} + \Delta t_{scatter}. \quad (1)$$

In the case of intracloud emission, however, it is unclear what to expect for the value of  $\Delta t_{physical}$ .

We wish to measure the “lag,”  $\Delta t_{physical}$ , for IC and cloud-to-ground (CG) lightning which we define as the time from the RF peak to the onset of the optical signal. Optical onset we determine by subtracting the rise time (which includes the delay due to scattering) from the optical time of peak (“lag”  $\equiv \Delta t_{physical} = t_{opt\ peak} - t_{opt\ rise} - t_{rf\ peak}$ ). This results in a distribution of lags which ranges from  $-2$  ms to  $+1.3$  ms. The largest lags, either positive or negative, must be the result of incorrectly paired RF and optical signals. We therefore perform a sigma clipping of the 302 RF/optical coincident events, dropping from the database seven events for which the lag is more than  $3\sigma$  from the mean lag of the entire population. In Figure 5 we plot histograms of the remaining lags and mark the



**Figure 5.** Histograms of the RF-to-optical lag for (a) IC and (b) CG events. “Lag” (equation (1)) is defined as the time from the RF peak to the onset of the optical signal. The mean and its standard deviation is marked for each distribution.

mean and standard deviation, for ground strokes and in-cloud events. We know that  $\Delta t_{\text{scatter}} \geq 0$ . The data are therefore consistent with there being a physical delay between the RF peak and the optical signal onset of  $\Delta t_{\text{physical}} \approx 60 \mu\text{s}$  for ground strokes and  $\Delta t_{\text{physical}} \approx -33 \mu\text{s}$  for IC lightning. This value for the ground strokes is consistent with previous estimates [Suszcynsky *et al.*, 2000; Ganesh *et al.*, 1984]. This is also consistent with the finding of Jacobson *et al.* [2000] that ground strokes tend to be observed by FORTE up to  $\sim 50 \mu\text{s}$  after being detected by the NLDN (see that paper’s Figure 3). For the cloud discharges, negative lags suggest that the optical signal onset often precedes the RF peak. In Figure 6 we show some examples; these records are typical of those in which several cloud events occur in succession. If one extrapolates back from the optical peak to when the optical signal began, we see that often the optical pulses begin before the peak of the RF signal, and indeed some begin nearly simultaneously with their corresponding RF event. Because the optical onset still includes some small delay due to scattering, in many cases the optical pulse must have been emitted coincident with or even earlier than the RF emission.

We assume that to within the resolution of our measurements, the optical emission and current flow are simultaneous [Beasley *et al.*, 1983; Gomes and Cooray, 1998] and consider the optical emission onset as a proxy for the onset of current flow. IC lightning therefore appears to involve temporally extended, gradually increasing currents, which create optical waveforms which are broadened beyond what can be accounted for simply by scattering within the clouds [Light *et al.*, 2001].

### 3.4. General Observations

Several features in these waveforms become apparent as one sifts through hundreds of examples, which are difficult to quan-

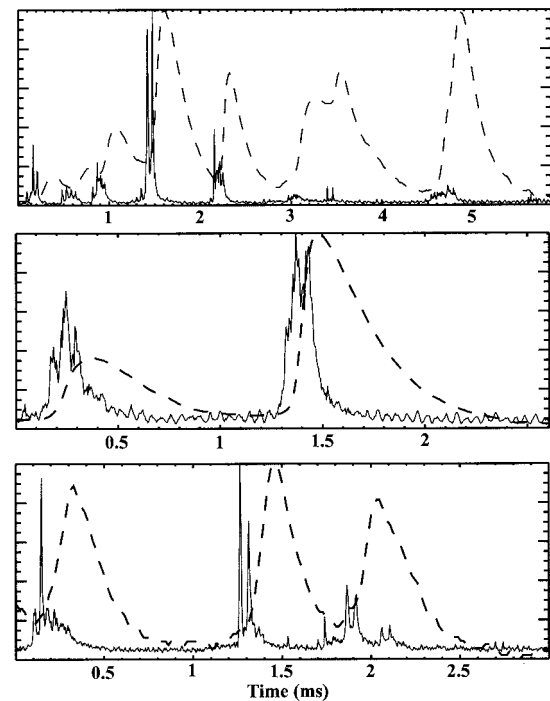
tify statistically but which could be called “commonly seen.” Below we briefly describe a few of these observations.

1. For initial negative return strokes, we often see low-level light preceding the main optical pulse, corresponding to the optical counterpart of the leader activity. (See Figures 7a and 7b for an example.) Also, we sometimes see structure in the optical leader, in which the light waxes near the leader onset, wanes, and then reasserts just before the return stroke. A similar pattern was seen in at least one stepped leader observed by Mazur *et al.* [1995]. In Figure 7a there is the suggestion of discrete leader steps, approximately 4 ms before the attachment, which gradually blur into continuous leader emission. This is not a commonly seen feature, perhaps because we do not often have several milliseconds of leader activity recorded for a return stroke.

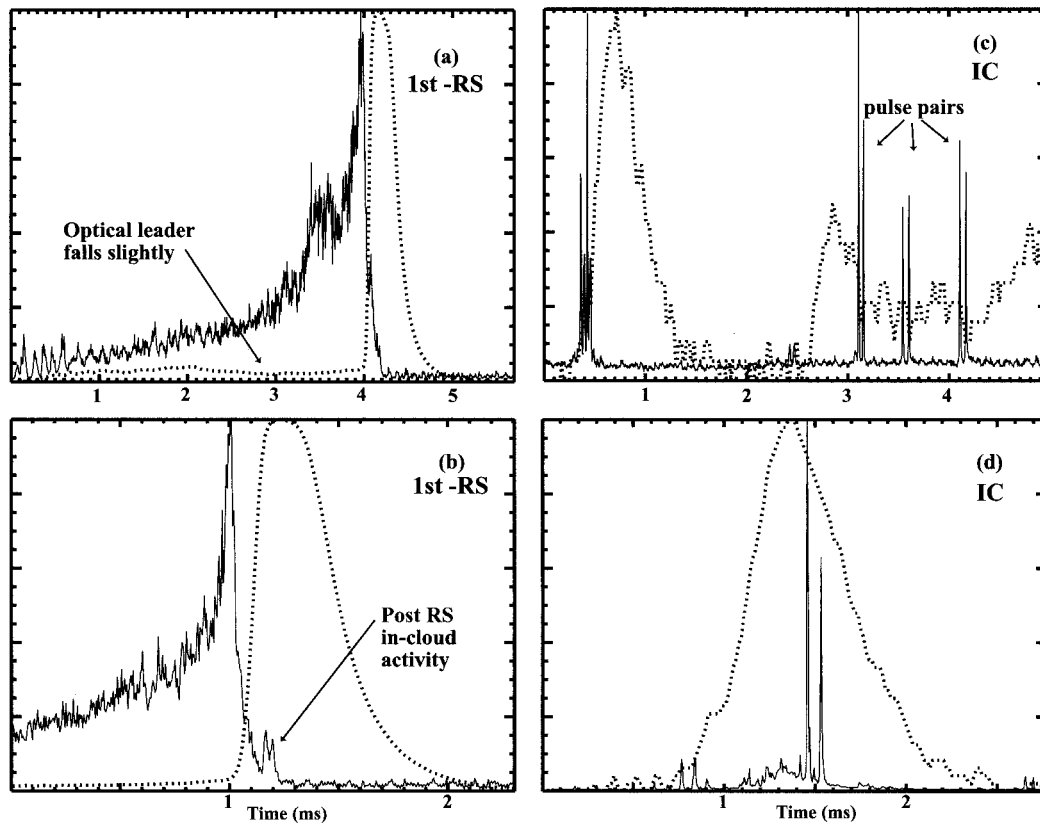
2. Initial negative return strokes are very commonly followed immediately (within 50–300  $\mu\text{s}$ ) by some form of cloud discharge, usually a doublet of NI events (Figure 7b).

3. We saw two cases (4%) where the optical counterpart to a first return stroke is double peaked, with the optical peaks spaced by  $\sim 700 \mu\text{s}$ . We note that Guo and Krider [1982] similarly saw that the optical signals from  $\sim 5\%$  of first return strokes had a second peak, but with no corresponding second peak in the  $E$  field signature. Those authors assume these secondary peaks to be caused by branches or M components.

4. The RF pulses of IC activity tend to occur in the context of extended multi-peaked optical emission, rather than to be associated with specific peaks of light (Figures 7c and 7d).



**Figure 6.** A few typical RF and optical coincident waveform sets, showing intracloud lightning. These are not full 8-ms records; we have excerpted subrecords for clarity. The RF and optical signals have been normalized by the peak emission in each record, to allow direct comparison in a single plot. The RF has been binned to 5- $\mu\text{s}$  resolution.



**Figure 7.** Examples of commonly seen features in the database, as described in the text. The optical and RF curves have 15- $\mu$ s and 5- $\mu$ s resolution, respectively.

#### 4. RF Pulse Pairs

In the self-triggered FORTE RF data, so-called “transionospheric pulse pairs” [Holden *et al.*, 1995] are among the strongest events seen, and we see few ground strokes. These pulse pairs are a VHF pulse and its reflection off the ground, each seen by the satellite after traversing slightly different paths and therefore the secondary (reflection) is delayed by an amount proportional to the event’s height off the ground [Massey and Holden, 1995; Massey *et al.*, 1998]. The event height can be calculated if one knows the latitude and longitude of the event and the position of the satellite. These present data are triggered by the OLS, and in them we see a high incidence of weak pulse pairs that would not have triggered the RF receiver on their own, while the most powerful events we see are initial negative return strokes. This reinforces the impression that impulsive in-cloud discharges in general are not associated with strong optical counterparts. Extended IC emission, however, typically includes several weak impulsive events and enough light to trigger the optical sensors. We therefore have a sample of pulse pairs unbiased by peak RF pulse power with which we can explore (1) the rate of occurrence of impulsive RF events and (2) the vertical distribution of lightning within each record or within each flash or storm using the event heights derived from the interpulse times. (Because all the data in this study are geolocated with the FORTE LLS, each pulse pair provides an event height estimate.)

To build a database of impulse parameters, we identify pulse pairs manually within each record, selecting the peaks of the primary and reflected pulse, and then in software calculate the

event height for each primary impulse. This procedure is straightforward for isolated pairs, but occasionally there are sequences of multiple impulses which complicate matters. We interpret these as pair multiplets, and accordingly, we group them into pairs whenever possible. Sometimes it is not possible to do so. For example, if only an odd number of impulses are obvious (e.g., due to poor signal-to-noise ratio), it becomes unclear which may be paired. Such cases are left out of the database.

There were, on average, seven impulse pairs found per flash, with an average rate of 1.2/ms, once they start occurring. (Often, the first few records in a flash will not have any impulses, and then there are several records containing IC impulses. We calculated the rate from the time of the initial pulse pair to the final one.) Table 2 lists some statistics for the 290 pulse pairs measured. The height shown is the event height, in kilometers, calculated by using the LLS geolocation. We define the “ratio” to be the ratio of the peak power of the primary (first) impulse to that of the reflected impulse.

The peak of the primary impulse does not vary as a function of the event height, nor as a function of when the impulse occurs during the flash. The height spread within a single flash is typically less than 1 km but can range up to about 6 km (Figure 8). We looked at whether we could detect the bilevel structure in individual IC flashes [e.g., Shao and Krehbiel, 1996; Thomas *et al.*, 2001], but with only a few pulse pairs within any given flash with which to probe the event heights, this structure was not obvious. Figure 8 also shows the overall distribution of event heights. The distribution is fairly constant from 6 to 13

**Table 2.** General Statistics of 290 RF Pulse Pairs

	Height, km	Ratio of Peaks	RF Peak, mV <sup>2</sup> /m <sup>2</sup>	Rate, Pairs/ms	Number per Flash
Mean	10.12	1.32	0.081	1.15	7
Standard deviation	2.2	0.95	0.20	1.53	6
Median	10.20	1.12	0.031	0.70	5
Minimum	6.10	0.04	0.0017	0.02	1
Maximum	15.50	10.8	2.1	5.98	34

km but then falls off sharply with fewer than 10 events at 13–16 km.

## 5. Summary

We compared individual RF and optical pulses from lightning observed with the FORTE satellite. More than 80% of ground strokes showed obvious associated optical and RF signals; only ~50% of in-cloud events showed similar RF/optical correspondence. The peak RF and optical power in related pairs of pulses correlate over several orders of magnitude, although the relation is broad, owing presumably to losses of the optical signal by scattering in clouds. Ground strokes are among the strongest events seen, in both optical and RF, while impulsive in-cloud events are among the weakest.

Using the RF discharge as the time fiducial, we find that for ground strokes there appears to be a small delay between emission of the RF and optical signals,  $\langle \Delta t_{CG} \rangle = 59 \mu\text{s}$ . For in-cloud events, however, the optical signal onset often precedes the peak of the RF,  $\langle \Delta t_{IC} \rangle = -33 \mu\text{s}$ . This implies that the optical signal must have been emitted earlier than or coincident with the onset of the RF signal.

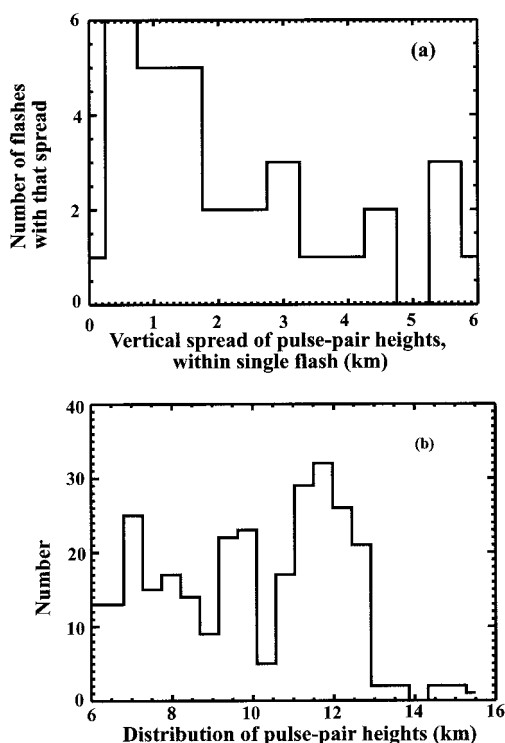
Optical emission from leader activity was commonly seen, and rather than monotonically increasing like the RF leader, the optical leader often decreases midway through and increases again near the time of the return stroke. While the RF and optical emission from return strokes typically appear as strong and unambiguous bursts, the RF pulses of IC activity tend to occur within the context of extended multi peaked optical emission.

Using RF pulse pairs due to reflection of a pulse off the ground, we estimate the heights of several in-cloud events. The height distribution ranges from 6 to 13 km and falls off sharply at higher altitudes.

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**Figure 8.** (a) Range of heights measured for RF pulse pairs which occur in the same flash. (b) Overall distribution of heights measured for all 290 pulse pairs.

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